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APPLICATION OF DUST FOR SPACE STRUCTURES

by Carl N. Klahr, Sylven N. Cutler, and Kalman Kalikstein

Prepared by
FUNDAMENTAL METHODS ASSOCIATES, INC.
New York, N. Y.

for

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ABSTRACT

This report is concerned with the physical properties and applications of small particles -particles whose masses range from 100 micrograms to 1 micro-microgram. It has been found in this work that dust particles have some unusual physical properties and that shaped dust collections or dust structures may be applicable to some tasks in space technology. A dust structure will be defined to be a spatial distribution of discrete particles whose relative geometry is maintained by the particle trajectories or by individual particle motion, and not by conventional cohesive forces which hold solids or liquids together. Therefore, dust configurations can be considered a new type of physical structural material, having properties often unlike those of solids, liquids, or gases. Various means can be used to maintain the gross relative geometry of the spatial distribution which constitutes the dust structure. Dust structures have unique properties across the entire thermal and electromagnetic energy spectrum, from optical frequencies through microwave and radio frequencies. Their inertial and mechanical properties as well as their gross material behavior are also quite unusual.

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SECTION 1
INTRODUCTION

This report is concerned with the physical properties and applications of small particles - particles whose masses range from 100 micrograms to 1 micro-microgram, with emphasis on the 10^{-6} gram to 10^{-9} gram mass range. We refer to such particles as dust, and to collections of such particles as dust structures. It has been found in this work that dust particles have some unusual physical properties, and that shaped dust collections or dust structures may be applicable to some tasks in space technology.

A dust structure will be defined to be a spatial distribution of discrete particles whose relative geometry is maintained by the particle trajectories or by individual particle motion, and not by conventional cohesive forces which hold solids or liquids together. Therefore, dust configurations can be considered a new type of physical structural material, having properties often unlike those of solids, liquids, or gases. Various means can be used to maintain the gross relative geometry of the spatial distribution which constitutes the dust structure.

Dust structures have unique physical properties across the entire electromagnetic energy spectrum from optical frequencies through microwave and radio frequencies. Their inertial and mechanical properties when viewed as a collective entity, as well as their gross material behavior, are also quite unusual.

A number of possible applications of dust structures can be suggested. At this time many of these possibilities are somewhat speculative. They will be described briefly in this report. Several of the applications however, have been subjected to sufficient analysis to permit their properties to be quantitatively assessed. Among the application areas for dust structures are the following: heat rejection radiators, protection systems against meteoroids, large-area optical scatterers, furlable microwave antennas, large-area radio telescopes, moon shelters, and large-area solar energy converters.

The unusual properties of dust were first realized from work on protection of space vehicles against meteoroids. It was found that dust can be several hundred times more effective on a unit mass basis than armor plate in providing protection against hypervelocity impact. A system called the "Dustwall" was invented for maintaining a continuous flow of dust outside the space vehicle. This is shown schematically in Figure 1. This dustwall is contained by mechanical circulation. Another type of dustwall would provide electrostatic containment for the dust. A dustwall can destroy an impinging hypervelocity pellet - for example, a meteoroid - by either vaporizing it, or by eroding it away. This erosion mechanism, which produces numerous micro-craters in the pellet, is effective even at low hypervelocities, e.g. 3 to 6 miles per second. It is these unusual properties of dust in hypervelocity impact interactions that suggest a more general consideration of the physical properties of small-particle materials.

Throughout the electromagnetic spectrum the one outstanding physical property of dust is its large interaction area per unit mass. The interaction area of a dust particle is at least equal to its geometrical area. The geometrical area per unit mass is given in Figure 2. For 10^{-9} gram particles of density 2.5, this gives a total surface area of 2,520 cm^2/gm, while for 10^{-12} gram particles the surface area is 25,200 cm^2/gm. This should be compared with the surface area of conventional structural materials, e.g. a plane sheet of 50 mil thick material has an area of 6 cm^2/gm. Thus there is an area-to-weight advantage of 500 to 1 to 5000 or more to 1 for dust over conventional structures.

This area advantage is obtained in the following portions of the electromagnetic spectrum:

a) optical
b) infrared
c) microwave and radio frequency reflection and scattering
d) radiation or absorption at any of the frequencies

The organization of this report will be as follows. The potential advantages and potential applications of dust structures will be described in Section 1.1. This section will describe the somewhat speculative applications which have not been analyzed quantitatively; it will also review briefly the more definitive applications whose quantitative analysis is given in greater detail in the subsequent sections.

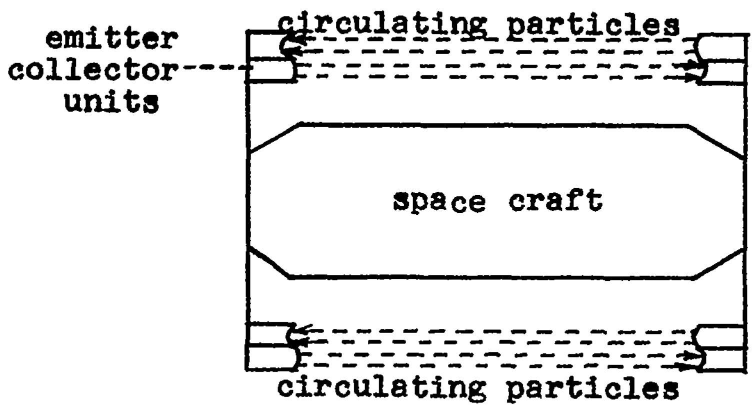


FIGURE 1. Schematic Representation of a Circulating Dustwall Configuration

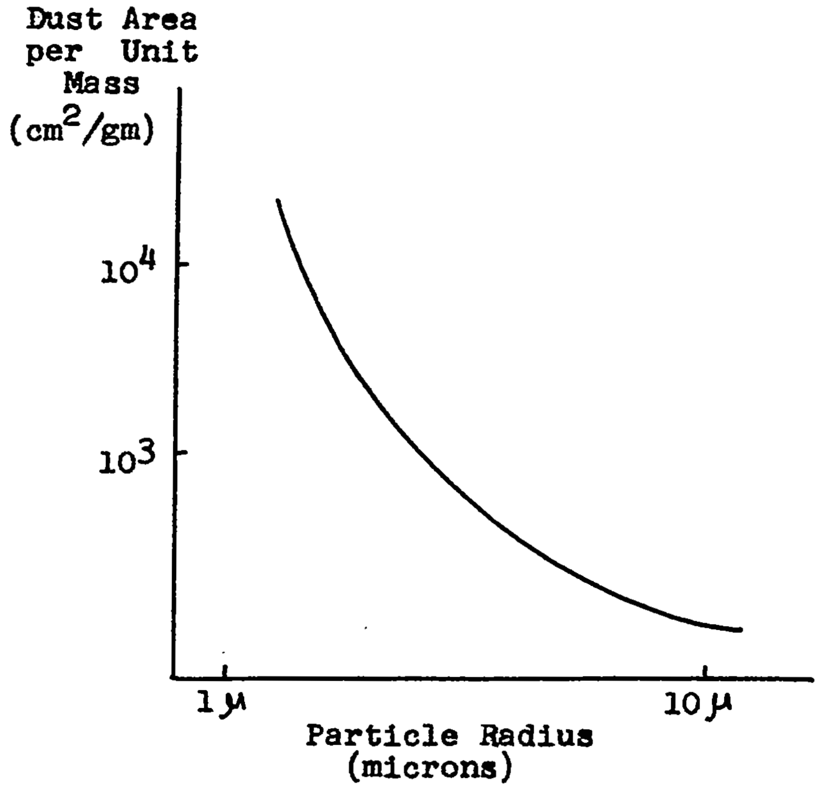


FIGURE 2. Area per Unit Mass Versus Particle Radius

A brief review of possible methods for producing dust structures is given in Section 1.2. These methods include (1) mechanical circulation of dust between emitters and collectors; (2) electrostatically contained or controlled dust structures; (3) controlled seeding of dust in force-free locations. These methods are also somewhat speculative inasmuch as no well-developed technology is available that has demonstrated the practicality of such practices. The feasibility of these methods (as distinguished from their practicality) has however been established by some experiments which will be briefly reviewed. For example, mechanical dust-walls have been fabricated and operated to maintain a continuous circulation of dust in vacuum for many hours.

The following three sections review those dust applications for which some detailed analysis has been performed. Section 2 presents the physics of optical applications of dust structures. Section 3 describes a thermal application of a dust structure in the form of a heat rejection radiator. Section 4 discusses the potential applicability of dust structures as microwave reflectors and radiators.

1.1 POTENTIAL ADVANTAGES AND APPLICATIONS OF DUST STRUCTURES

The foremost advantage of dust structures is that of large area per unit mass. This advantage will be applicable to any technical situation in which surface area is a figure of merit. This includes the following: thermal radiation and absorption; optical and electromagnetic scattering, radiation, and absorption; mechanical interaction cross section. This advantage of large area per unit mass extends across the entire spectrum of electromagnetic applications, from the ultraviolet to the audio frequency range. The interaction area per unit mass can exceed that for conventional structures by three or four orders of magnitude.

The second advantage of dust structures is that of inertial properties. When one speaks of the inertial properties of a dust structure he is referring to the capability of changing or altering the dust structure. Such inertial effects are much smaller than for conventional structures, i.e. one can change or alter the dust structure with much less force and energy applied than for conventional structures, both because of the much smaller masses to be controlled, and because of one's ability to do this simply by "turning off" the structure by terminating the particle trajectories and subsequently re-establishing it in its new mode.

A third important advantage of dust structures is that they offer structural integrity under severe conditions of stress, especially at high temperatures. Ordinary stress considerations do not apply to dust structures since the structural configuration is maintained by the trajectories of individual particles. Therefore, the particle may be a brittle solid, ordinarily useless for structures, or it may be a liquid. In a dust radiator for example, one can consider high temperature materials like boron, which have high specific heat, operated at temperatures where sodium or NaK would vaporize.

The physical properties of dust described above have suggested a number of potential dust structure applications. A list of these appears below. At the present time, some of these applications are somewhat speculative. We have carried out a preliminary survey of these potential applications in which some of the most obvious questions and advantages have been investigated. While one cannot be certain of the practicability or even of the feasibility of these dust structures before a detailed design has been made, a number of them may offer substantial advantages over conventional structures for the same purposes. Furthermore, a number of these applications offer technological possibilities that cannot otherwise be obtained. These applications are:

1. Heat rejection radiators comprised of a dust circulation system. One can show that a recirculating dust radiator structure can be 10 to 1000 times as effective as conventional space radiators in terms of heat rejection per unit mass.

2. Use of a dustwall for protection against meteoroid impact. It has been shown that individually separated dust particles are far superior to solid material in stopping hypervelocity pellets. A very low dust density, e.g., 10 to 20 grams per square meter of surface area to be protected, is sufficient to stop meteoroids of masses less than 2 milligrams. Such a dustwall can be optically transparent. One can estimate that an entire system to protect a large space vehicle against meteoroids would weigh only 1% or 2% as much as armor plating for equivalent protection.

3. "Furlable" microwave scattering antennas or transmit-receive antennas for microwave communications. The advantages are: large area per unit mass, ready furlability, and independence of conventional structural problems.

4. Large-area radio-telescopes, large dust structures with dimensions ranging from hundreds of meters to many miles. The very large areas attainable with reasonable mass and without structural problems may permit the construction of large radio-telescopes of unparalleled sensitivity.

5. Large-area optical scattering surfaces as illuminators or as reference beacons. The advantage is large area per unit mass and freedom from conventional structural problems. A convenient orbital location for such a large-area optical illuminator would be at the libration points of the earth-moon system -positions of dynamical stability for the dust configuration.

6. "Dust moon houses", i.e., dynamic structures of circulating dust for meteoroid protection on the moon surface, as well as for optical shadowing and retention of radiation. This application makes use of the hypervelocity impact shielding characteristics of dust. (A surface mass density of 10 to 20 grams per square meter provides protection against meteoroids up to 2 milligrams in mass.)

7. Dust solar energy converters, composed of a circulation of semiconductor dust particles, each with a P-N junction, which converts solar energy into electrical energy. For example, if gallium arsenide particles with appropriate doping patterns are used, the individual particles will convert solar energy into microwave energy by means of the Gunn effect. The microwave energy would then be focussed to a central collection point. Such a structure would be much more efficient in terms of energy converted per unit mass than a conventional solar energy converter.

8. Use of dust structures for providing even illumination by optical scattering, e.g., outside a space vehicle or on the dark surface of the moon.

9. Optical shutters for space vehicle windows, composed of electrostatically charged dust. The application of an electric potential will rapidly change the optical transmittivity from transparent to opaque or vice versa, by covering the window with dust.

10. Use of an electrostatically-contained distribution of charged dust particles (this has been termed a "dustgas") as an electrostatic shock absorber. It would be used to decelerate a space vehicle in landing, i.e., to cushion a hard landing.

11. Electrostatically-contained dust to be used as a rigid structural element. The presence of electrostatic forces arising from externally applied stresses will maintain the rigidity of such a structural element. It may have a very favorable strength-to-mass ratio.

12. Control of weather in selected regions of the earth by placing dust in the upper mesosphere and the thermosphere, altitudes of 80 km to 200 km. Small dust particles will remain suspended for long periods; the noctilucent clouds are just such a phenomenon. If sufficient dust is present to substantially alter the solar radiation entering the atmosphere over a distance of many square miles, appreciable weather effects may be produced. Preliminary estimates indicate that substantial dust can be emplaced at a relatively low cost. An important problem however, will be the predictability of the weather effects produced.

A brief description of several dust structures applications will be given in the remainder of this section. A more detailed analysis will be given in Sections 2, 3, and 4 of this report.

A schematic diagram of a dust radiator is shown in Figure 3. This is a structure in which dust is maintained in circulation between emitters and collectors; its purpose is the rejection of heat by thermal radiation. At the emitter the dust absorbs heat from the low-temperature end of a heat engine. As the dust passes in transit between emitter and collector, it radiates its heat into space. The large surface-to-mass ratio of small-particle dust gives it a special advantage in radiation. One can show that a recirculating dust radiator structure can be 10 to 1000 times as effective as conventional space radiators in terms of heat rejection per unit mass.

A "furlable" microwave scattering or transmit-receive antenna will consist of a pattern of dust beams, each produced by an emitter-collector pair extended from a space vehicle, either by means of a tow rope or from an independently powered satellite vehicle. The advantages of such an antenna are: large area per unit mass, a variety of shapes, and independence of conventional structural problems.

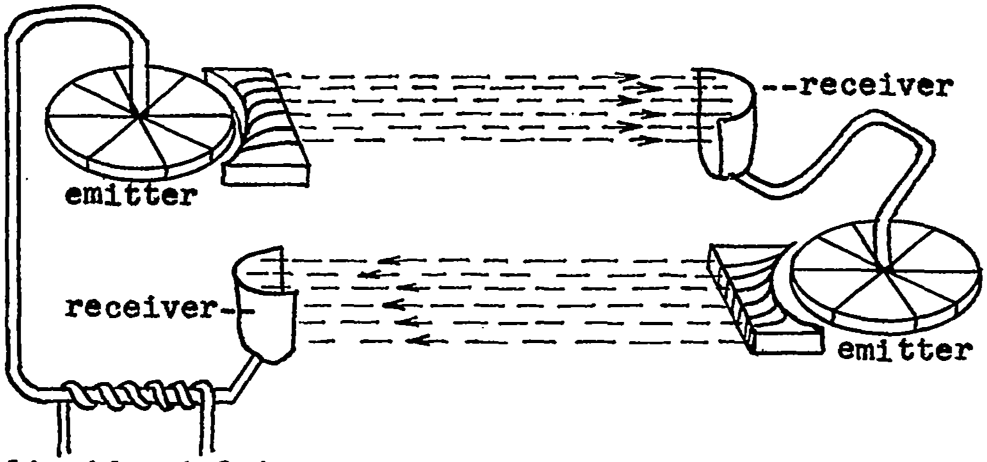


FIGURE 3. Dust Structure for Heat Radiation

The use of dust for electromagnetic antennas may offer great advantages over conventional structures (e.g., metal sheet, rod, ribbon, or dielectrics) although there may also be some considerable difficulties in making dust antennas practical. Because of the low mass requirements, extremely large antennas and arrays can be formed for small weight penalties. A mass of 200 pounds per square mile is an example of what may be attainable. Furthermore, dust antennas do not suffer from the usual structural problems of conventional antennas - for example, distortion and breakage due to thermal radiation imbalance, due to construction difficulties, and due to meteoroid hazards.

Large-area optical scatterers constitute another significant application of dust structures. Such a "dust moon" would consist of a large-area dust surface to comprise an optical mirror. Estimates indicate that a mass of 400 pounds per square mile may give substantially complete optical reflection. Thus an optical beacon or large-area reflector in synchronous orbit could intercept 10^{-3} radian of arc (.06 degree) for a total mass of 50 tons of dust. Such an artificial moon, if made from any conventional metallized film material, would be much more massive; it would also have conventional structural problems.

The advantages in area per unit mass of large-area optical surfaces can be calculated. An advantage factor of at least 100 to 1 in area per unit mass over alternative methods can be demonstrated. The use of such dust materials at stable orbital locations, i.e. the libration points of the earth-moon orbit looks particularly attractive.

Another advantageous optical application is that of an optical diffusing dust atmosphere to provide illumination on the away-from-the-sun side of a large space vehicle. The dust atmosphere can be set up by circulating dust, for example by use of emitter-collector systems.

Another potentially important application of the dustwall for shielding against meteoroids is a structure which may be called the dust moonhouse. Such a structure appears practical. The only competing method for large structures on the moon which would be safe from the great meteoroid hazard there is the use of caves within the moon's crust.

A schematic diagram of a toroidal dust moon house is shown in Figure 4. This structure would produce a dust surface mass density of 10 to 15 grams per square meter, for protection against meteoroids, or of 100 to 300 grams per square meter for opacity to optical radiation. The dust would be collected in a circumferential trough and recirculated to the emitting center.

1.2 TECHNOLOGIES FOR PRODUCING DUST STRUCTURES

It is important to point out how dust structures can be physically produced. Three general methods for producing dust structures can be listed:

1. Mechanical circulation of dust between emitters and collectors which are placed on space vehicles, on satellite vehicles, or on extended booms or towlines. A combined emitter-collector module would be used. Two such modules can give continuous circulation. The emitter uses a mechanical impeller from which particles are emitted with a specified initial velocity. The emitted particles are directed into a collimation system from which they depart travelling in parallel, rectilinear paths. This dust-beam is received at a collector, conducted to a nearby emitter, and returned by the foregoing process to a collector near the point of origin. This system forms a mechanical dustwall.

   Mechanical dustwalls have been built and operated for periods of hours. In hypervelocity impact tests, the effectiveness of dustwalls for shielding against meteoroids has been demonstrated. In addition, considerable experimental work has been done on the mechanics of dust emission and collimation, on the measurement of dust densities, and on dust recirculation. A schematic diagram of a mechanical dustwall is shown in Figure 5.

2. Electrostatically contained or controlled dust, in which electrically charged dust is deflected or contained within charged grids. This category includes a diverse number of possibilities:

   a) The "dustgas" configuration for containment of charged particles within a special system of charged grids

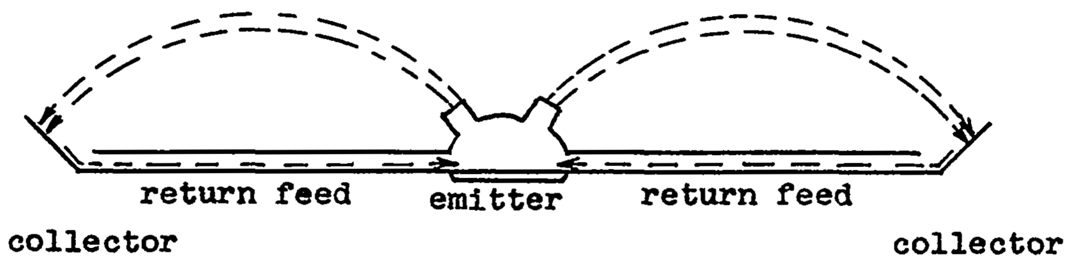


FIGURE 4. Toroidal Dust Structure for Moon Shelter

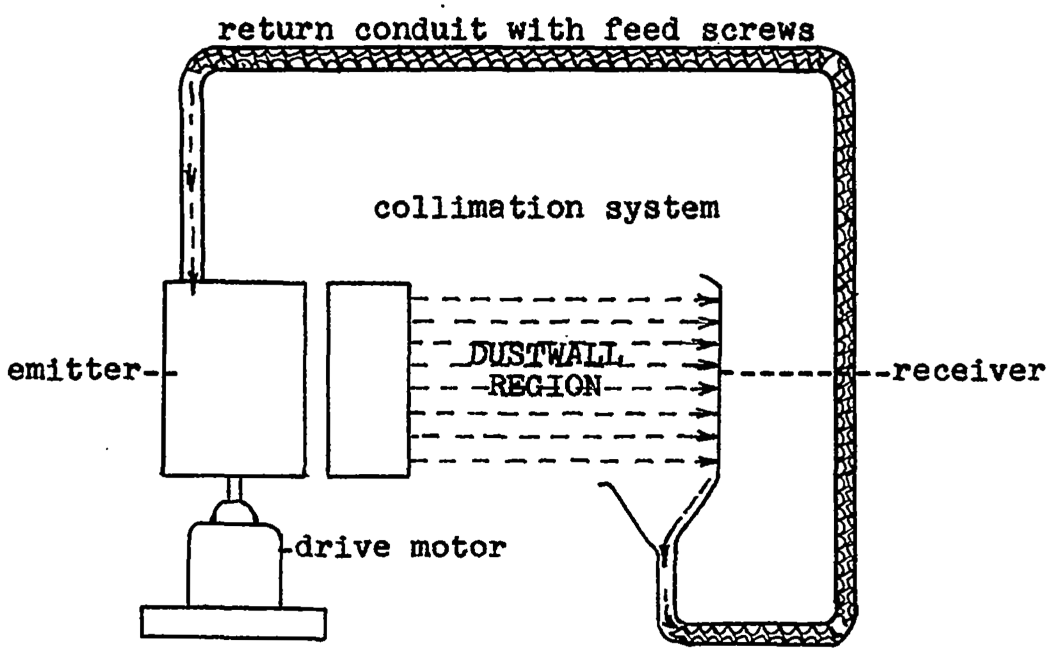


FIGURE 5. Mechanical Dustwall System

b) Mechanical circulation of charged dust particles to obtain improved collimation

c) Control of trajectories of charged dust particles by application of electrostatic forces between emitters and collectors over large distances

d) Establishment of "electrostatic atmospheres" of charged dust particles orbiting an oppositely charged central vehicle.

In the area of electrostatic techniques, dustgas containment systems have been designed, dust electrification methods have been investigated, and dust charging apparatus has been investigated and designed. Apparatus for dust electrification experiments has been constructed. Electrostatic dust charging guns have been built and operated with great efficiency.

3. The "seeding" of dust in specified positions. Once placed properly with due regard to all perturbing forces, such configurations will remain in place, provided that the dust is seeded with the proper relative velocities and initial conditions. A new technology is required for accurate placement of the dust. The accuracy required in dust velocity specification would require a technology which is closely related to the rendezvous and docking technology which is currently being developed. Three variations of this dust seeding technique are:

   (1) The seeding of dust in force-free locations, e.g. at the earth-moon libration points.

   (2) Accurately controlled emission of dust from a moving space vehicle to achieve a desired dust shape by virtue of the motion of the emitter.

   (3) Seeding of dust followed by shaping of an initially formless configuration. The shaping can be achieved by using a small robot ship with a "dust scoop" which removes dust from regions where it is unwanted. Figuratively one can say it "machines" the dust volume. For example, a dust parabola could be formed in this manner.

For the large-area coverage desired in the present applications, dust structure formation techniques described above must be re-examined and further developed. Of prime concern is the degree of directivity and collimation which can be obtained in any system as well as the cost in weight and power requirements. The length of time of cohesion of a dust structure is also an important criterion. With regard to this "stability time" criterion, it should be noted that dust structures of two types are feasible. One, based upon a continuously circulating system such as the mechanical emitter-collector concept, can be maintained indefinitely as long as the prime mover system is kept in operation with negligible dust loss. The other system, based upon the "seeded volume" concept, may gradually disperse. The lifetime of such systems must be examined for each application.

For applications such as thermal radiators, which require comparatively small-volume dust distributions, the present mechanical dustwall technology seems to be directly applicable although considerable development work will be necessary. The main conceptual problems of dust distribution technology are concerned with the large-area applications and the special problems they raise - namely those of collimation and lifetime. Data on the degree of collimation obtainable and methods of obtaining a dust beam with the desired degree of collimation should form one phase of an experimental dust technology program.

The collimation of the dust propagation can be secured either mechanically or electrically. A mechanical collimation of 10^{-5} radian is probably obtainable. Furthermore, use of dust particles with a large length-to-width ratio would facilitate mechanical collimation. Electrical collimation would use alternate charged beams of opposite sign.

Let us consider a typical mechanical system for dust beam formation and collection. Our experience has shown that an efficient system of dust beam formation is one which uses a vaned rotor onto which dust is introduced in a controlled manner. The dust exits at approximately 45° with respect to the rotor perimeter and has a velocity whose magnitude is dependent upon the rotor velocity. Collimation surfaces in the form of a "dust lens" redirect the particles into parallel ray beams. Typical experiments for a 4 inch diameter rotor produce particle beams moving with speeds of the order of meters per second. In space, for practical beam densities giving no particle collisions, such beams would travel along straight-line paths until received at the collector. A mile-long beam would require several hours passage time between emitter and collector. The slower the particle velocity, the less total dust is required in circulation for a given density. However, for fast steering of an antenna, one would require either faster particle velocity if the antenna were to be re-oriented, or more reasonably, re-orientation of the much smaller antenna feed system rather than of the antenna itself. The question of particle velocity is one which must therefore be solved to achieve a compromise between efficient dust containment and the requirements of the application considered.

After passage through the active volume, the dust beams fall upon a collector surface whence they are returned to the emitter. When the particles are returned from a second emitter located adjacent to the collector, the return stream participates in the active volume. A system somewhat like this has been operated in the laboratory. The device is constructed almost wholly of plastics or other light-weight materials. Our 4 inch diameter rotor was designed for a dust flow rate of 50 to 100 grams per second using 20 micron Al_2O_3 particles. The weight of such an emitter-collector system can be of the order of 2 pounds, corresponding to a system mass of 10 grams per 1 gram per second flow rate. Our experimental systems have been somewhat heavier since these are "breadboard" devices in which no attempt at optimization has been made. Both weight and power per unit mass can be reduced by a factor of perhaps 100 or more with the development of a more sophisticated technology.

In the experimental devices described above, no special efforts were made to get well-directed beams and no measurements of collimation uniformity were attempted. Good collimation and even dust distribution however were evident.

SECTION 2

OPTICAL APPLICATIONS OF DUST STRUCTURES

2.1 PHYSICS OF DUST-ELECTROMAGNETIC INTERACTION

Optical applications of dust structures are described in this section. The following topics are covered: (1) physics of a single dust particle interacting with electromagnetic radiation, (2) various dust structure applications.

Throughout the electromagnetic spectrum the one outstanding physical property of dust is its large interaction area per unit mass. The interaction area of a dust particle is approximately equal to its geometrical area. The geometrical area per unit mass is given for spherical particles by

$$\frac{A}{m} = \frac{4\pi r^2}{m} = \frac{4\pi}{m}\left(\frac{3m}{4\pi\rho}\right)^{2/3}$$

where m is the mass of the dust particle, ρ is its density, r is its radius, and A is its cross sectional area. For 10^{-9} gram particles of density 2.5, this gives a total surface area of 2520 cm^2/gram, while for 10^{-12} gram particles the surface area is 25200 cm^2/gram. This should be compared with the surface area of conventional structural materials, e.g., a plane sheet of 50 mil thick material has an area of 6 cm^2/gm. Thus there is an area-to-weight advantage of 500 to 1 to 5000 or more to 1 for dust over conventional structures.

This area advantage is obtained in the following portions of the electromagnetic spectrum:

a) optical
b) infrared scattering
c) microwave and radio frequency reflection and scattering
d) radiation or absorption at any of the frequencies

When particles are widely separated as compared to a wavelength, the effective cross sectional area will vary strongly with the frequency of the radiation. This property (e.g., in Rayleigh scattering) can be used for preferential scattering of certain wavelengths, as in an optical filter application.

Particles can scatter or reflect radiation in either the forward or the backward direction, depending on their material composition as well as on their size. Metallic particles tend to scatter primarily backward, i.e., to reflect. Dielectric particles tend to scatter forward as well as backward. Such forward scattering is equivalent to transmission through a medium with a dielectric constant determined by the density as well as the composition of the dust. The ratio of forward-to-backward scattering can be determined by appropriate selection of the size and composition of the particles.

It is apparent that the selection of dust particle size, material, and mean inter-particle distance can be used to exercise wide-ranging control over the interaction of the dust with electromagnetic radiation for a variety of applications: reflection, scattering, radiation and absorption, from the ultraviolet to the radio and audio frequency ranges. The major advantage of dust in this interaction is its large area per unit mass, which can exceed that of conventional structures by three, four, or five orders of magnitude.

Single Dust Particle Interacting With Electromagnetic Radiation

The pertinent physical properties to be considered in particle-electromagnetic radiation interaction are C_{sca}, the scattering cross section, $i_1(\theta)$, the intensity of the component of the scattered light polarized in the direction perpendicular to the plane of scattering, and $i_2(\theta)$, the intensity of the scattered light polarized in the direction parallel to the plane of scattering.

Throughout this discussion, it will be assumed that the radius a of the spherical dust particle is 1 micron. There are three regions of interest in the electromagnetic spectrum:

1) $\lambda \ll a$ corresponding to the optical region

2) $\lambda \gg a$ corresponding to radio frequencies and microwaves

3) $\lambda \approx a$ corresponding to infrared radiation

In the optical region, the scattering cross section for both dielectric and metallic particles is

$$C_{sca} = 2\pi a^2$$

For dielectric spheres, the scattered intensity components $i_1(\theta)$ and $i_2(\theta)$ (where θ is the scattering angle) are given by

$$i_1(\theta) = \frac{(ka)^2 \ \epsilon_1^{\ 2} \ \sin\Upsilon \cos\Upsilon}{\sin\theta \ \ (d\theta/\Upsilon)}$$

$$i_2(\theta) = \frac{(ka)^2 \ \epsilon_2^{\ 2} \ \sin\Upsilon \cos\Upsilon}{\sin\theta \ \ (d\theta/d\Upsilon)}$$

where $k = 2\pi/\lambda$ = wave number

a = dust particle radius

Υ = angle of incidence

The Fresnel reflection coefficients r_1 and r_2 are defined as follows:

$$r_1 = \frac{\sin\Upsilon - m\sin\Upsilon'}{\sin\Upsilon + m\sin\Upsilon'}$$

$$r_2 = \frac{m\sin\Upsilon - \sin\Upsilon'}{m\sin\Upsilon + \sin\Upsilon'}$$

where m = index of refraction

Υ' = angle of refraction

$\epsilon_1 = r_1$ for $p = 0$

$\epsilon_1 = (1-r_1^2)(-r_1)^{p-1}$ for $p = 1, 2, \ldots$

$\epsilon_2 = r_2$ for $p = 0$

$\epsilon_2 = (1-r_2^2)(-r^2)^{p-1}$ for $p = 1, 2, \ldots$

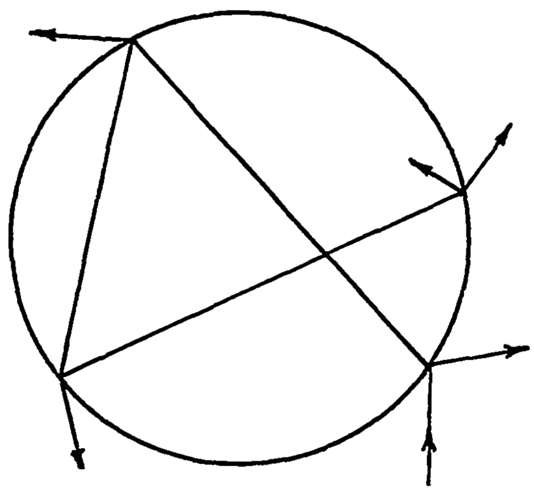


FIGURE 6. Path of a Light Ray Through a Sphere where it is Divided by Reflections and Refractions

As shown in Figure 6, the energy is divided by successive reflection or refraction among the single rays denoted by $p = 0, 1, 2, 3, \ldots$. It is seen that the scattering pattern is not isotropic for dielectric particles.

For metallic particles the index of refraction m approaches infinity and $i_1(\theta) = i_2(\theta)$ approaches $1/4\ (ka)^2$ which is independent of θ.

Thus, a smooth, totally reflecting spherical particle with radius large compared to the wavelength, scatters light (by reflection) isotropically.

In the radio-frequency and microwave region ($\lambda \gg a$), the scattering is of the Rayleigh type. For dielectric particles in an electromagnetic field, the radiation is due to electric dipoles. One has

$$C_{sca} = \frac{8}{3} \pi k^4 a^6 \left| \frac{\epsilon^2 - 1}{\epsilon^2 + 2} \right|$$

where ϵ is the dielectric constant ($\epsilon = m^2$). The scattering intensities are

$$i_1(\theta) = \left(\frac{\epsilon^2 - 1}{\epsilon^2 + 2} \right) (ka)^6$$

$$i_2(\theta) = \left(\frac{\epsilon^2 - 1}{\epsilon^2 + 2} \right) (ka)^6 \cos^2 \theta$$

The total scattered intensity is the same in the forward and backward directions.

A metallic particle ($m = \infty$), on the other hand, emits magnetic dipole and quadrupole radiation besides electric dipole radiation. This results in a non-isotropic scattering pattern.

$$C_{sca} = \pi a^2 \left[\frac{10}{3} (ka)^4 + \frac{4}{5} (ka)^6 + \ldots\right]$$

and
$$i_1(\theta) = (ka)^6(1-\cos\theta) + \frac{1}{4} \cos^2\theta$$
$$i_2(\theta) = (ka)^6(\cos^2\theta - \cos\theta + \frac{1}{4})$$

The above equations indicate that the scattering is predominantly backward. The forward scattered intensity is 1/9 the backward scattered intensity.

Consider infrared radiation, ranging from $8\text{x}10^{-1}$ to $3\text{x}10^{3}$ microns. As the wavelength becomes comparable to the particle radius, assumed to be 1 micron, scattering becomes predominantly forward for a dielectric dust particle. Table 1 gives the relative intensity scattered in the forward ($\theta=0$), backward ($\theta=\pi$), and $\theta=\pi/2$ directions as a function of ka.

TABLE 1. RELATIVE SCATTERING INTENSITY AS A FUNCTION OF ka

θ	ka = 0.01	ka = 0.1	ka = 0.5	ka = 1
0	5.0×10^{-14}	5×10^{-8}	1.2×10^{-3}	2.3×10^{-1}
$\frac{\pi}{2}$	2.5×10^{-14}	2.5×10^{-8}	5.0×10^{-4}	3.6×10^{-2}
π	5.0×10^{-14}	4.9×10^{-8}	7.8×10^{-4}	1.9×10^{-3}

θ	ka = 2	ka = 5	ka = 8
0	4.3	9.8×10^{2}	7.5×10^{3}
$\frac{\pi}{2}$	2.5×10^{-1}	2.7	7.1
π	2.0×10^{-2}	1.3	0.9

For metals in the infrared region, the real and imaginary parts of the index of refraction are very large and nearly equal:

$$m = n - in', \qquad n \doteq n'$$

where n and n' are the real and imaginary terms respectively. The particle acts practically as a reflector.

2.2 OPTICAL APPLICATIONS OF DUST STRUCTURES

Large-area optical scatterers constitute a significant potential application of dust structures. The dust structure would constitute a diffuse scatterer like the moon. Such a structure would be called an optical beacon, an artificial moon, or an optical diffuser.

The mass required for such a dust structure can be calculated using the formula for area per unit mass given at the beginning of this section. Dust particles of mass 10^{-12} gram are sufficiently massive to be unaffected by light pressure, the Poynting-Robertson effect, and other small forces. Using a particle mass of 10^{-12} gram and a particle density of 0.1 gram per cm^3, one finds that 600 pounds of dust particles will completely cover a square mile, assuming the scattering cross section is equal to the geometric cross section. Since the scattering cross section will be about 1.5 times the geometric cross section, a more realistic mass estimate is 400 pounds per square mile. This mass per unit area is at least 50 times less than that required by any alternative method.

Consider an optical beacon or large-area reflector in synchronous orbit at a distance of 22,000 miles from earth. If the scatterer is circular with a radius of 9 miles, the dust distribution would comprise 50 tons. It would intercept 10^{-3} radian of arc (0.06 degree). Such an artificial moon, if made from conventional metallized film, would be much more massive than 50 tons. For example, a 5 mil thick film would weigh at least 450 tons per square mile, leading to a total mass of over 100,000 tons.

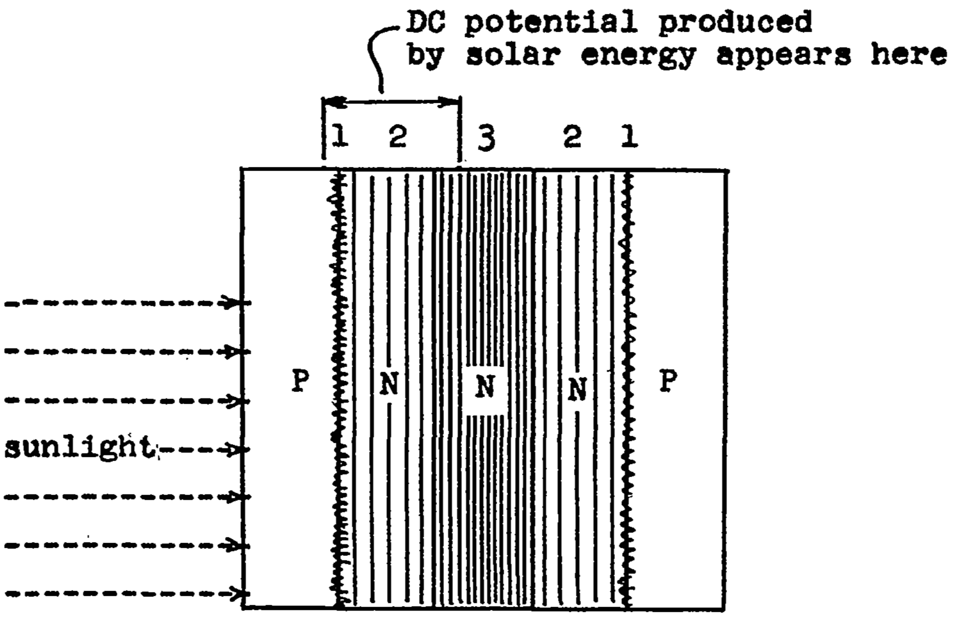
A particularly favorable location for the dust optical beacon would be at a stable orbital location, i.e., at the libration points of the earth-moon orbit, where gravitational and dynamic forces would work together to preserve the stability of the structure.

Another advantageous optical application is that of an optical diffusing dust atmosphere to provide illumination on the away-from-the-sun side of a large space vehicle. The dust atmosphere can be set up by circulating dust, for example by use of emitter-collector systems.

One can also consider the application of dust structures for conversion of sunlight into microwave energy, and then into DC electrical energy. This can be produced by a semiconductor solar cell. It is most efficient to make such semiconductor cells out of dust particles, in order to obtain large area per unit mass. The power produced by a semiconductor P-N junction solar converter is proportional to its area, and the area of a given mass of material can be maximized in the form of a dust. Each dust particle would have a P-N junction. One has the problem of collecting the power produced by the dust particles. This can be accomplished by converting the DC power to microwave power and radiating the microwave power to a central rectifier feed point where it is converted back to DC. Figure 7 shows how a novel semiconductor effect (the Gunn effect) is built into a gallium arsenide dust particle to do this.

Gallium arsenide is a semiconductor which can function both as a P-N junction solar converter, and as a Gunn effect generator to produce microwaves. It would be used in the form of small dust particles, each of which would have a junction configuration like that shown in the figure. Methods have been studied for fabricating such semiconductor dust particles by standard methods of semiconductor technology. The P-N junctions can be inserted by diffusion. Appropriate control of the diffusion process will give the doping profile shown in Figure 7.

The photovoltaic effect produces a potential across the lightly-doped N type region. In an N type region in gallium arsenide, when a DC electric field of 3000 volts per cm or more is applied, spontaneous microwave oscillations are produced whose frequency is governed by the thickness of the



LEGEND

1- P-N junction regions

2- low N type doping regions (high resistivity N type). These are the Gunn oscillator regions.

3- high N type doping region

FIGURE 7. Solar Energy Converter: Cross-Section of a Doped Semiconductor Dust Particle

layer. In gallium arsenide a photovoltage of 1 volt will be produced. A sizable part of this voltage will be across the lightly-doped N type region whose thickness will be about 1 micron.

A potential of 0.3 volt will give the 3000 volts per cm required for the Gunn effect. The dust particle then becomes a microwave generator. The large surface area of the dust suspension will then produce a large microwave power. One can specify conditions that will make the dust configuration act as a microwave cavity, so that phase-locking of the power produced by the individual dust particles can be achieved. The entire dust distribution between emitter and collector will then constitute a single microwave generator and antenna whose output can be focussed on a central rectifier feed horn which will reconvert the microwave power into direct current. Alternatively, this large-area microwave generator can be used as an antenna radiator for communications purposes.

SECTION 3

THERMAL APPLICATIONS OF DUST STRUCTURES

3.1 DUSTWALL RADIATOR

In this section, a heat rejection radiator comprised of a dust circulation system will be described. Such a system is shown schematically in Figure 3. In this structure, dust is maintained in circulation between emitters and collectors for the purpose of heat rejection by thermal radiation. Heat is absorbed by the particles at the emitter from the low temperature end of a heat engine. As the dust passes in transit between the emitter and collector, it radiates its heat into space. The large surface-to-mass ratio of small particles gives dust a special advantage in radiation. It will be shown that a recirculating dust radiator structure can be 10 to 1000 times as effective as conventional space radiators in terms of heat rejection per unit mass.

In the dust radiators we have considered, the dust receives its heat in a liquid-metal-to-dust heat exchanger before entering the emitter. This requires the emitter to operate at high temperatures. Dust from the collector is recirculated to the heat exchanger by a second emitter-collector module. By using dust materials having high specific heat, e.g., boron or graphite, the heat capacity of the dust radiator may be maximized. Another alternative is the following: The liquid-metal coolant can be broken into dust-size droplets in a showerhead emitter. These liquid drops will solidify in radiating, thus adding their heat of fusion to their specific heat in giving a large overall heat capacity. The important advantage of dust is its large value of radiating area per unit mass. For a 5 micron boron particle (boron has a high specific heat per unit mass and can be used at high temperatures) one obtains about 2500 cm^2 per gram of dust particles. In contrast, a fin and tube type radiator will have an area-to-mass ratio of a few cm^2 per gram, giving a ratio of advantage of dust to conventional radiators of thousands to one, as will be shown below.

Heat Transfer to Dust Particles: The heat transferred per unit time from liquid-metal to dust circulating in a heat exchanger can be calculated as follows: The total radiator mass is

$$M_t = M_e + M_d \tag{1}$$

where M_t = radiator mass (equipment + dust)

M_d = mass of dust

M_e = mass of equipment

M_d consists of two parts: M_c, the dust mass circulating through the dustwall, and M_r, the mass of dust in the recirculation system and reservoirs.

$$M_d = M_c + M_r \tag{2}$$

In terms of the dustwall geometry, one has

$$M_c = n\ h\ w\ L\ m \tag{3}$$

where n = number of particles per unit volume

h = weight of dustwall

w = width of dustwall

L = length of dustwall

m = mass of dust particle

The rate of heat absorption by the dust in the liquid-metal-to-dust exchanger is given by

$$\frac{dH_a}{dt} = C_p(T_o - T_c)\frac{dM_c}{dt} = C_p(T_o - T_i)\frac{v}{L}\ M_c \tag{4}$$

where dH_a/dt = heat absorbed per unit time

C_p = dust specific heat at constant pressure

T_i = initial dust temperature

T_o = final dust temperature (temperature of exchanger

v = dust velocity

Heat Radiated in a Dustwall: The heat radiated per unit time by a single particle at a point x in the dustwall, where x is in the direction of the dust circulation, is

$$\frac{dH_r}{dt} = m\ C_p \frac{dT}{dt} = m\ C_p\ v\ \frac{dT}{dx} = \sigma E T^4(x) A_d V_f \tag{5}$$

where dH_r/dt = rate of heat radiation

σ = Stefan-Boltzmann constant, $= 5.67 \times 10^{-5}$ erg/cm^2 deg^4 sec

E = emissivity of dust $\quad 0 \leq E \leq 1$

A_d = area of dust particle

V_f = view factor

In order to evaluate the average heat radiated by the dustwall, we must determine the average of the fourth power of the temperature, T^4_{av}.

$$T^4_{av} = \frac{1}{L} \int_0^L T^4(x)\ dx \tag{6}$$

But from equation (5)

$$\frac{dT}{T^4} = -\ \alpha\ dx \tag{7}$$

where

$$\alpha = \frac{\sigma E\ A_d V_f}{m C_p v}$$

Thus, $$T^4_{av} = -\ \frac{1}{\alpha L} \int_0^L \frac{dt}{dx}\ dx = \frac{T_o - T_i}{\alpha \cdot L} \tag{8}$$

The total heat radiated by the dustwall is

$$\frac{dH}{dt} = \sigma EA(T_{av}^4) = \frac{\sigma EA}{\alpha L}(T_o - T_i) \tag{9}$$

where A = dust radiating area = $nhwLA_dV_f$. Since $A = \frac{M_c}{m} A_dV_f$, one has

$$\frac{dH}{dt} = \frac{\sigma E}{\alpha L} \frac{M_c}{m} A_dV_f(T_o - T_i) \tag{10}$$

T_i can be expressed in terms of the heat exchanger temperature and the radiator parameters. From equation (7) one has

$$T_i = \left(\frac{1}{T_o^3} + 3\alpha L\right)^{-1/3} = \left[\frac{1}{T_o^3} + 3\frac{\sigma EA_dV_f}{mC_pv} L\right]^{-1/3} \tag{11}$$

<u>Figure of Merit:</u> The radiator figure of merit $\mathcal{M}$ (the power radiated per unit radiator mass) is

$$\mathcal{M} = \frac{dH}{dt} \frac{1}{M_t}$$

Since our system is in equilibrium, dH/dt equals dH_a/dt (in equation (4)). Therefore, we can either use expression (10) or (4) to determine $\mathcal{M}$. It follows from equations (1), (2), (3), and (4) that

$$\mathcal{M} = C_p(T_o - T_i) \frac{v}{L}\left[1 + \frac{M_r + M_e}{nhwLm}\right]^{-1} \tag{12}$$

The basic problem is to maximize $\mathcal{M}$ and then to compare it with other types of radiators.

Let us write equation (12) in terms of the system parameters T_o, x, μ, M_r (in our system M_r M_r-M_e), F and τ where

$$x = \frac{C_p v}{L}$$

$$\mu = 3\sigma E V_f \frac{A_d}{m}$$

$$F = \frac{dM_c}{dt} = \frac{v}{L} \quad nhwLm$$

$$\tau = \frac{M_r}{F} \qquad \text{(the technology index)}$$

τ is a measure of the dust circulation technology. The better the technology, the smaller is τ. Equations (11) and (12) can be written as

$$T_i = \left[\frac{1}{T_o^3} + \frac{\mu}{x}\right]^{-1/3}$$

$$\mathcal{M} = x(T_o - T_i) \left[1 + \frac{\tau x}{C_p}\right]^{-1} \qquad (13)$$

Of course, the figure of merit is an optimum if $M_c >> M_r$, or

$$\mathcal{M} = x(T_o - T_i)$$

and $$\frac{dM}{dt} = - x\frac{dT_i}{dx} - T_i = 0$$

The following tables give the results of an analysis of the dust radiator in terms of the system parameters. On the basis of these tables, the following observations can be made:

1. The higher the heat-exchanger temperature T_o, the greater the figure of merit.

2. Table 4 indicates that the greater the mass flow rate, the greater the heat dissipation, regardless of heat-exchanger temperature.

3. Tables 5 and 6 show that in order to get comparable heat dissipation from a conventional radiator, the mass flow rate must be about 3 times that required for the dust radiator.

4. Table 7 shows that for all values of the operating temperature, as τ decreases, $(1/M_d)(dH/dt)$ decreases.

5. Table 9 indicates that as $x = C_p(v/L)$ decreases from its optimum value, $(1/M_d)(dH/dt)$ decreases for all values of T_o.

TABLE 2

DUST RADIATOR FIGURE OF MERIT UNDER OPTIMUM CONDITIONS

T_o (°K)	x_{max} (watt/gr °K)	ΔT (°K)	$(1/M_d)(dH/dt)$ (watt/gr)
1400	1.50×10^2	9.0×10	1.35×10^4
1000	7.0×10	5.5×10	3.85×10^3
800	4.0×10	4.0×10	1.60×10^3
500	1.5×10	1.5×10	2.25×10^2
300	4.3	8	3.44×10

Assumptions:

1. $\tau = 0$
2. No material restrictions
3. $\mu = 1.42 \times 10^{-8}$ watt/gr $(°K)^4$. (This corresponds to a dust particle 1 micron in radius and having a density of 1 gram/cm^3.)
4. $(1/M_d)(dH/dt) = x\Delta T \qquad (\Delta T = T_o - T_i)$

TABLE 3

FIGURE OF MERIT FOR CONVENTIONAL TUBE-AND-FIN RADIATOR

Radiator Metal		Columbium
Coolant		Liquid Potassium
T_o		$1035^\circ K$
$\frac{1}{M_d}\frac{dH}{dt}$	Tube and Fin 1-side	1.51 watt/gram
$\frac{1}{M_d}\frac{dH}{dt}$	Tube and Fin 2-sides	2.1 watt/gram

TABLE 4

DUST RADIATOR HEAT DISSIPATION VERSUS MASS FLOW RATE

$T_o = 800^\circ K$		$T_o = 1000^\circ K$		$T_o = 1400^\circ K$	
dH/dt (kw)	F (lb/sec)	dH/dt (kw)	F (lb/sec)	dH/dt (kw)	F (lb/sec)
$1.6x10^3$	44	$3.85x10^3$	77	$1.35x10^4$	165
$8.0x10^2$	22	$1.92x10^3$	38.5	$6.75x10^3$	82.5
$3.2x10^2$	8.8	$7.70x10^2$	15.4	$2.70x10^3$	33
$1.6x10^2$	4.4	$3.85x10^2$	7.7	$1.35x10^3$	16.5
$8.0x10$	2.2	$1.92x10^2$	3.85	$6.75x10^2$	8.25
$4.8x10$	1.32	$1.15x10^2$	2.31	$4.05x10^2$	4.95

Assumptions:

1. Optimum Conditions
2. Dust is graphite, boron, or beryllium and $C_p = 2$ joules/gm$^\circ$K
3. $\mu = 1.42x10^{-8}$ watt/gram $(^\circ K)^4$. (This corresponds to a dust particle .4 micron in radius and having a density of 2.54 gm/cm^3.
4. $\tau = 0$

TABLE 5

DUST RADIATOR HEAT DISSIPATION VERSUS MASS FLOW RATE

	$T_o = 800^oK$	$T_o = 1000^oK$	$T_o = 1400^oK$
dH/dt (kw)	F (lb/sec)	F (lb/sec)	F (lb/sec)
$5x10^3$	13.8x10	10.0x10	6.1x10
$10x10^3$	27.6x10	20.0x10	12.2x10
$50x10^3$	$13.8x10^2$	$10.0x10^2$	$6.1x10^2$
$100x10^3$	$27.6x10^2$	$20.0x10^2$	$12.2x10^2$

Assumptions:

1. Optimum Conditions
2. Dust particles are graphite, boron, or beryllium
3. $\mu = 1.42x10^{-8}$ watt/gm $(^oK)^4$. (This corresponds to a particle .4 micron in radius and having a density of 2.54 gram/cm^3.)
4. $\tau = 0$

TABLE 6

CONVENTIONAL RADIATOR HEAT DISSIPATION VERSUS MASS FLOW RATE

dH/dt (kw)	F (lb/sec)
5×10^3	2.4×10^2
10×10^3	4.8×10^2
50×10^3	2.4×10^3
100×10^3	4.8×10^3

Assumptions:

1. Conventional tube-and-fin radiator made of columbium using liquid potassium as coolant
2. $C_p = .836$ joule/gram ^oK
3. $T_o = 1035^oK$
4. $\Delta T = 55^oK$
5. $dH/dt = C_p \Delta T\ F$

TABLE 7

DUST RADIATOR FIGURE OF MERIT AS A FUNCTION OF EMITTER TECHNOLOGY

T_o (^oK)	x (watt/gm ^oK)	Technology Index τ (sec)	$(1/M_d)(dH/dt)$ (watt/gm)
1400	1.5×10^2	10	1.80×10
		1	1.78×10^2
		10^{-1}	15.9×10^3
		10^{-2}	7.7×10^3
1000	7.0×10	10	1.1×10
		1	1.07×10^2
		10^{-1}	8.55×10^2
		10^{-2}	2.85×10^3
800	4.0×10	10	8.0
		1	7.6×10
		10^{-1}	5.35×10^2
		10^{-2}	1.34×10^3
500	1.5×10	10	2.96
		1	2.65×10
		10^{-1}	1.28×10^2
		10^{-2}	2.20×10^2
300	4.3	10	1.52
		1	1.09×10
		10^{-1}	2.84×10
		10^{-2}	3.35×10

Assumptions:

1. Optimum Conditions
2. Dust used is boron
3. $\mu = 1.42 \times 10^{-8}$ watt/gm $(^oK)^4$ (This corresponds to a dust particle .4 micron in radius and having a density of 2.54 gm/cm^3.)
4. $C_p = 2$ joules/gm ^oK
5. $$(1/M_d)(dH/dt) = x \, \Delta T \, \frac{1}{1 + (\tau x / C_p)}$$

TABLE 8

v/L VERSUS T_o FOR BORON DUST PARTICLES UNDER OPTIMUM CONDITIONS

$(1/M_d)(dH/dt)$ (watt/gm)	T_o (^oK)	ΔT (^oK)	v/L (sec^{-1})
1.35×10^4	1400	9.0×10	$.705\times10^2$
3.85×10^3	1000	5.5×10	3.27×10
1.60×10^3	800	4.0×10	1.88×10
2.25×10^2	500	1.5×10	$.705\times10$
3.4×10	300	8	2.01

Assumptions:

1. $\tau = 0$
2. $C_p = 2$ joules/gm ^oK
3. $\mu = 1.42\times10^{-8}$ watt/gm $(^oK)^4$ (This corresponds to a dust particle .4 micron in radius and having a density of 2.54 gm/cm^3.
4. $v/L = (1/C_p \Delta T)(1/M_d)(dH/dt)$

TABLE 9

RADIATOR FIGURE OF MERIT FOR BORON
UNDER NON-OPTIMUM CONDITIONS

T_o (°K)	x (watt/gm °K)	ΔT (°K)	v/L (sec^{-1})	$(1/M_d)(dH/dt)$ (watt/gm)
1400	1.5×10^2	9.0×10	$.705 \times 10^2$	1.35×10^4
	1.5×10	4.8×10^2	$.705 \times 10$	7.2×10^3
	1.5	9.35×10^2	$.705$	1.4×10^3
1000	7.0×10	5.5×10	3.27×10	3.85×10^3
	7.0	3.05×10^2	3.27	2.12×10^3
	7.0×10^{-1}	6.40×10^2	$.327$	4.50×10^2
800	4.0×10	4.0×10	1.88×10	1.60×10^3
	4.0	2.30×10^2	1.88	9.20×10^2
	4.0×10^{-1}	5.00×10^2	$.188$	2.00×10^2
500	1.5×10	1.5×10	$.705 \times 10$	2.25×10^2
	1.5	1.15×10^2	$.705$	1.73×10^2
	1.5×10^{-1}	2.86×10^2	$.0705$	4.3×10
300	4.3	8	2.01	3.44×10
	4.3×10^{-1}	10	$.201$	4.3
	4.3×10^{-2}	5.5×10	$.0201$	2.36

Assumptions:

1. $\tau = 0$
2. $\mu = 1.42 \times 10^{-8}$ gm $(°K)^4$ corresponding to a dust particle radius of .4 micron and having a density of 2.54 gm/cm^3.
3. $x = C_p(v/L)$ where $C_p = 2.12$ joule/gm °K
4. $(1/M_d)(dH/dt) = x\,\Delta T$
5. The first line corresponds to optimum conditions.

TABLE 10

DUST RADIATOR HEAT DISSIPATION VERSUS MASS FLOW RATE FOR NON-OPTIMUM CONDITIONS

$T_o = 800^oK$		$T_o = 1000^oK$		$T_o = 1400^oK$	
dH/dt (kw)	F (lb/sec)	dH/dt (kw)	F (lb/sec)	dH/dt (kw)	F (lb/sec)
9.20×10^2	4.15	2.28×10^3	7.2	7.2×10^3	15.4
4.60×10^2	2.07	1.06×10^3	3.6	3.6×10^3	7.7
2.00×10^2	.415	4.50×10^2	.72	1.4×10^3	1.54
1.00×10^2	.207	2.25×10^2	.36	$.7 \times 10^3$	.77

Assumptions:

1. Non-optimum conditions
2. $\gamma = 0$
3. $\mu = 1.42 \times 10^{-8}$ watt/gm $(^oK)^4$ corresponding to a dust particle of radius .4 micron and density 2.54 gm/cm^3.

SECTION 4

ELECTROMAGNETIC APPLICATIONS OF DUST STRUCTURES

4.1 DUST ELECTROMAGNETIC ANTENNAS

In this section, some preliminary concepts will be considered for use in space of configurations of micron size particles as electromagnetic antennas. For electromagnetic scattering applications, one should not be restricted to spherical particles. Long cylindrical particles whose diameters are micron size will be more effective in electromagnetic reflection than small spherical particles.

It can be experimentally demonstrated that long cylindrical needles with very narrow diameters will be effective in reflecting microwave radiation. It has long been known (and used in countless applications) that total closed coverage of an area is not required for the effective use of a surface as an efficient reflector. Thus a grid of wires spaced closer than the free space wavelength forms a reflector for an incident wave whose electric polarization is parallel to the axes of the wires. For example, a wire area coverage of only 0.1% can provide a geometrical reflection coefficient better than 0.9 if there are 40 or more wires per wavelength. This mechanism can be understood physically in a number of ways. For example, one may consider the space between wires as forming a number of waveguides below cutoff. Essentially then the reflection is due to the equivalent material coupling capacitance and inductance between wires, much as the propagation (or non-propagation) characteristics for any waveguide can be understood by an equivalent circuit basis. The scattering and resultant reflected wave from the array is much greater than that due to the total wire cross section alone. The important effect is the mutual coupling. In a similar manner a collection of particles can also serve as an equivalent line below or above cutoff to provide almost complete reflection or transmission with some equivalent dielectric property.

Knowing that the metallic wire grid has almost the same reflection as a solid metal surface, one next considers that separation of the individual wires of the grid will have only a small effect on the reflection as long as the individual wires have a length comparable to a wavelength. In the case of spatial distribution of dust needles or wires, the random nature of the array should permit good reflection from even shorter wire segments than in the case of a grid.

To summarize, for optimum electromagnetic scattering, the best dust particle will be needle-shaped with length much greater than diameter. Such a dust particle may be termed a "whisker". Metal whiskers have been grown as single crystals with much greater tensile strength than the usual polycrystalline form of the metal. A technology for making and handling such long dust whiskers can probably be developed. Thus the advantage of dust particles, large area per unit mass, can be had for electromagnetic reflection. One would use such dust whiskers with mass of 10^{-6} gm to 10^{-7} gm, and with a length comparable to the wavelength. The replacement of a wire grid by these discrete dust whiskers would probably have a minimal effect on the reflection coefficient of the surface, if the whiskers were arranged in a random array.

A second point should be noted with regard to dust configurations as opposed to other types of reflectors, grids included. The dust configuration is essentially a random collection of particles although the boundaries can be fairly well defined. Because of this, the resultant propagation and reflection will have coherent and incoherent components. However, the incoherent component can be made very small for the distribution considered, as shown in Section 4.3, so this really need not be a problem. The result can only be a small deterioration of the antenna properties.

The dust antenna is a "seeded" or contained spatial distribution of micron or submicron particles in a pattern which is shaped by the containment parameters to provide the desired reflection and/or propagation characteristics. It is conceivable that almost any of the standard antenna types such as parabolas, long wavelength wires and arrays of wires such as directive firing rhomboids, dielectric antennas, etc. may be formed. In particular, because of the low total mass required (for example, corresponding to the 200 lb/mile^2 for reflectors) extremely large antennas and arrays can be projected. Further, these do not suffer from the usual structural problems of connectional antennas due to the very lack of a solid supporting structure. Thus distortion and breakage due to thermal radiation and imbalance, destruction by meteoroids, etc. are not problems. One can list the advantages to be obtained with dust antennas as follows:

1) The possibility of extremely large antennas or arrays of antennas with the consequent high gain and resolution obtained with a relatively small total mass.

2) Maintenance of antenna integrity independent of thermal or meteoroid flux. Certain other problems such as "solar wind" effects, air drag, residual components of gravity, etc. which have to be considered might play important roles here however. Preliminary investigations have shown that these other forces will be sufficiently small in many cases, or containment and shaping schemes can be provided to make these forces ineffective.

3) Capability of orienting and reorienting antennas rapidly and with minimum power expenditure.

Dust antennas can be classed basically as of three distinct types when the specific operating functions are considered. These are:

1. Area coverage antennas
2. Individual beam antennas
3. Dielectric antennas

These three types can be described as follows:

1. Equivalent reflectors representing large area focussing, both cylindrical and spherical, horns of all types, and reflective grids and zone plates, among others. These antennas are formed of spatial dust distributions covering areas which have the shapes listed above. The cover may be complete, i.e., in the sense that the dust distribution covers the entire area forming the parabola for example, or it may be incomplete, wherein the dust distribution only partially covers an area. An example of incomplete coverage is a structure in which a reflecting surface is formed by a number of closely-spaced but separate "beams" of dust, much like a grid.

2. Separate beams or wire-like distributions of dust to simulate equivalent wires or rods. These may be arranged as separate wires of specific lengths as a dipole antenna for example, or as arrays of dust beams simulating a grid-like array of wires.

3. Dust distributions which simulate dielectric antennas in the form of lenses, dielectric rod antennas or surface wave devices.

A number of methods can be considered for setting up and maintaining the dust antenna configuration. The specifics of any method will depend critically upon the type of antenna to be formed and on the available technology. In general terms however, one can enumerate the methods as follows:

1) The continual circulation of dust in the form of dust "beams" provided by either mechanical or electrical emitters and collectors* This system is ideal for the equivalent wire type antennas, dielectric rod antennas, and others.

2) The seeding of dust in place to form the desired configuration. Once placed properly, with due regard to perturbing forces such as small gravity components, etc., spatial distribution of dust will maintain its configuration provided that the dust is seeded with the proper relative velocities and initial conditions.

3) Seeding of dust specifically in volumes where outside forces can contain the resultant formation. An example of such a position might be the earth-moon libration points.

4) Seeding followed by shaping of the dust distribution. (The shaping may be performed only initially or it may be continuous to provide continued correction of the dust distribution.) The shaping can be achieved by using a small robot space ship with a scoop which moves about the region removing dust from regions where it is not wanted. For example, a dust parabola could be formed in this way.

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* Dust beams have been produced and operated routinely using mechanical emitters and collectors for application in the testing of the dustwall concept for meteoroid protection.

A further aspect of dust antennas is the method of feeding and receiving the signal from the antenna. This again depends upon the particular type of antenna. Those which are essentially reflectors and focussers, such as the parabola, can use a small feed at the focus as does any such antenna. Since this is a small element, it need not be composed of dust but may be a conventional feed placed on a robot space vehicle which is stationed at the focus. This space vehicle will also contain the various other elements necessary for processing and transmitting signals to earth. Such a feed may be moved within certain latitudes to provide some degree of scanning of the antenna. Equivalent wire types of antennas or dielectric rod antennas on the other hand, would make use of other types of exciters. The dielectric rod essentially supports a surface wave mode, the signal from which would be obtained from a solid surface wave emitter. For these and equivalent wire configurations, the signal must be derived from field components or displacement current rather than conduction in the wire (the equivalent dust wire). A horn may be connected to a source by tapering the horn down to a conventional or over-size waveguide, itself made of dustwalls. The load in the waveguide can then be a detector, made of conventional waveguide components which are located in the dust waveguide.

An important problem is the amount of incoherent microwave reflection produced by a diffuse dust structure, i.e., a dust reflecting surface. A detailed calculation is given in Section 4.2 which shows that for practical dust densities, incoherent reflection will not be a problem.

A discussion of geometric configurations for dust antennas is given in Section 4.3.

4.2 INCOHERENT REFLECTION FROM DUST ANTENNAS

An important problem related to diffuse reflecting surfaces is that of incoherent reflection. A reflecting dust antenna is such a diffuse structure. A series of calculations is given in this section which show that as long as the mean width of dust beams is small in comparison to a wavelength, the incoherent reflection is not important.

In order to calculate the ratio of incoherent to coherent power, we will consider a distribution of dust particles about a line AB, as shown in Figure 8. Let x be the perpendicular distance of a dust particle from the line and θ the angle that the incident radiation makes with AB. The final result is practically independent of the form of the distribution, whether Gaussian, delta, or step function. Assume that the dust distribution G is normal (Gaussian) in the direction of x.

$$G(x) = \frac{1}{\sqrt{2\pi h^2}} e^{-x^2/2h^2} \qquad (14)$$

where h is the width of the dust region along the direction of propagation.

The scattered field due to a single scatterer is given by

$$E_s = \frac{\ell E}{r} e^{ikx \sin\theta}$$

where E = incident field amplitude

ℓ = scattering length of dust particle
where $\ell \cdot \ell^*$ is the scattering cross section

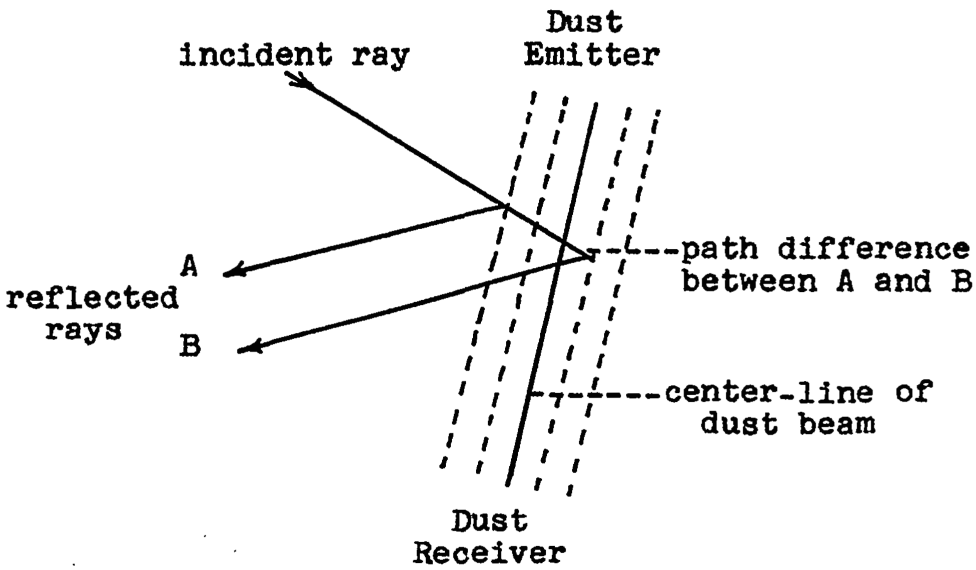
$k = 2\pi/D$ = wave number

r = distance from scatterer to point of observation

The scattered power is given by

$$\int_{-\infty}^{\infty} |E_s|^2 G(x)\,dx = \int \left|(E_s - \bar{E}) + \bar{E}\right|^2 G(x)\,dx$$

$$= \overline{\left|E_s - \bar{E}\right|^2} + \left|\bar{E}\right|^2 + \overline{E(E_s - \bar{E})^*} + \overline{(E_s - \bar{E})\,\bar{E}^*}$$



Path difference between A and B becomes
a phase difference

FIGURE 8. Incoherent Scattering from Dust Antenna

Since the cross terms vanish, one has

$$\int_{-\infty}^{\infty} |E_s|^2 \, G(x) \, dx = |E_s - E|^2 + |\bar{E}|^2 \tag{16}$$

E, the coherent amplitude due to all particles is

$$\bar{E} = A \int_{-\infty}^{\infty} E_s \, G(x) \, dx \, ds$$

$$= f \int_{-\infty}^{\infty} E_o \, e^{ikx \sin \theta} \frac{e^{-x^2/2h^2}}{\sqrt{2 \pi k^2}} \, dx$$

$$= f \, E_o \, e^{-(hk \sin \theta)^2/2} \tag{17}$$

where A is the number of particles per unit area in the incident beam, and ds is an element of area. $f = \int A \, ds$ is the fractional opacity of the dust. In equation (16), $|E-E_s|^2$ represents the scattered incoherent power and $|\bar{E}|^2$ stands for the scattered coherent power. In the incoherent term the intensities add, while in the coherent term the amplitudes add. Now

$$|\bar{E}|^2 = f^2 \, E_o^2 \, e^{-(hk \sin \theta)^2} = f^2 \, E_o^2 \, \rho^2$$

where $\rho = \bar{e}^{(hk \sin \theta)^2/2}$

Also $$\overline{|E_s - \bar{E}|^2} = \overline{(E_s - \bar{E})(E_s^* - \bar{E}^*)} = \overline{|E_s|^2} - |\bar{E}|^2$$

and

$$|E_s|^2 = \int E_o^2 \frac{\bar{e}^{x^2/2h}}{\sqrt{2\pi h^2}} dx = E_o^2$$

Thus

$$\left|E_s - \bar{E}\right|^2 = E_o^2(1 - f^2 \rho^2)$$

The ratio of incoherent to coherent power is given by

$$R = \frac{1 - f^2 \rho^2}{f^2 \rho^2}$$

The opacity f is given by $N h \sigma = f$

where N is the number of particles per unit volume and σ is $\mathfrak{q} \cdot \mathfrak{q}^*$, the scattering cross section. Consequently, R is a function of the particle size, density of particles (or spacing between particles) and frequency of incident radiation.

Of course, the thickness of the dustwall is related to f. The distance between particles is $r \cdot a$ where r is a positive number. Now

$$N = \frac{1}{\left(\frac{ra}{2}\right)^3}$$

thus

$$h = \frac{f(ra)^3}{8\sigma}$$

If $r \cdot a < \lambda$, particles closely spaced compared to wavelength, then $\sigma = \pi a^2$ (independent of size of particle), and

$$h = \frac{f\, r^3\, a}{8\sigma}$$

Table 11 gives the incoherent power ratio versus several dust parameters for spherical particles. It is expected that the case of spherical particles gives a more pessimistic estimate of the incoherent component than the more realistic case of cylindrical dust particles.

TABLE 11

FRACTION OF INCOHERENT POWER VERSUS FREQUENCY AND DUST DENSITY

Frequency (megacycles)	Incoherent Power Density: Mean Spacing-10 Radii, Particle Size 1 micron	Incoherent Power Density: Mean Spacing-10 Radii, Particle Size 20 microns	Incoherent Power Density: Mean Spacing-100 Radii, Particle Size 1 micron
30	6.3×10^{-12}	2.5×10^{-9}	6.3×10^{-6}
5,000	1.7×10^{-8}	7×10^{-5}	0.17
10,000	7×10^{-8}	2.8×10^{-4}	0.98

Assumptions:

Fraction of geometric area covered by dust is 0.1
Incidence of radiation is normal.

4.3 GEOMETRIC CONFIGURATIONS FOR DUST ANTENNA STRUCTURES

Two general types of dust antenna structures can be considered: (1) "furlable" microwave scattering antennas or transmit-receive antennas attached to the space vehicle; (2) large-area dust antenna structures in space with dimensions ranging from hundreds of meters to many miles.

A furlable microwave scattering or transmit-receive antenna will consist of a pattern of dust beams, each produced by an emitter-collector pair extended from a space vehicle, either by means of a tow rope or from an independently powered satellite vehicle. The advantages of such an antenna are: large area per unit mass, a variety of shapes, and independence of conventional structural problems. The use of dust beams in such an antenna is very similar to the use of long rods or wires as electric dipoles. Hence such a configuration is relatively familiar.

Large-area dust structures are of interest for radio telescopes or for antennas for hyper-long distance applications. A radio telescope is used to study the radio waves received on earth from a variety of astronomical objects. No radio source gives anything but a small amount of radio power flux at the surface of the earth. The sources radiate noise-like signals and their power fluxes vary from 10^{-22} to 10^{-26} watts per square meter (of collecting area of the antenna) per cycle per second (of radiometer bandwidth). It is thus clear that collecting areas of thousands of square meters are necessary when weak radio sources must be accurately measured.

Parabolic Dust Structures

One of the most widely used microwave antennas is the parabolic reflector. This configuration has very advantageous focussing properties, because the distance traveled by any ray from the focus to the parabola, in a plane perpendicular to the parabola axis, is independent of its path. Usually, to obtain this focussing property it is specified that the parabolic surface must be quite smooth in terms of the wavelength, e.g., the root mean square deviation of the reflecting surface from its ideal parabolic contour must be less than 1/8 of a wavelength.

This condition may be difficult to achieve with a dust surface. Such an imperfection will result in lower gain than the theoretical attainable value for the parabola dimensions. On the other hand, the lower gain will be compensated by the greater reflected power due to the large surface area achievable with a dust structure.

Smoothness of the parabolic surface however, may be less important for a dust structure. It is pointed out in Section 4.2 that a dust structure surface may be indefinite to within a fraction of the wavelength without any substantial penalties in incoherent power. This implies that the smoothness criterion is less important for a dust surface; hence deviations from an ideal parabolic shape will tend to be less important for a parabolic dust structure.

Typical quantitative indices for ideal parabolic structures are tabulated in Tables 12 and 13. Width and shape of the major lobe of the radiation pattern for a parabola depend upon the size and shape of the mouth of the parabola, and the variation of field intensity and phase over the aperture.

TABLE 12

BEAM WIDTHS OF PARABOLIC ANTENNAS

Shape of Mouth	Field Distribution Across Mouth	Width of Major Lobe: Between Nulls	Width of Major Lobe: Between Half-Power Points
Rectangular	Uniform	$\frac{115^\circ}{L/\lambda}$	$\frac{51^\circ}{L/\lambda}$
Rectangular	Sinusoidal along L	$\frac{182.5^\circ}{L/\lambda}$	$\frac{68^\circ}{L/\lambda}$
Circular	Uniform	$\frac{140^\circ}{L/\lambda}$	$\frac{58^\circ}{L/\lambda}$

In Table 12, L is length of a rectangular mouth or diameter of a circular mouth in the direction of interest. The gain is given by

$$G = \frac{k\, 4\pi A}{\lambda^2}$$

where A is the area of the antenna, λ the wavelength, and k is a constant. k takes into account any non-uniformity of magnitude and phase in the field distribution across the aperture of the parabola, and also any failure of the illuminating antenna to radiate all its energy against the reflecting surface. For constant intensity and uniform phase, one has $k = 1$. Under practical conditions, k will be of the order 0.5 to 0.7. The gain and beam width at different frequencies are given in Table 13 for $D = 1000$ meters.

TABLE 13

BEAM WIDTH AND GAIN VERSUS FREQUENCY

Shape of Mouth	Field Distribution	Width Between Half-Power Points	Gain $k = 0.5$	Frequency (mc)
Rectangular	Uniform	1.5°	7,000	10
Rectangular	Uniform	0.5°	60,000	30
Rectangular	Uniform	0.15°	7×10^5	100
Circular	Uniform	1.5°	5,500	10
Circular	Uniform	0.5°	50,000	30
Circular	Uniform	0.15°	5.5×10^5	100

Thus for a 1000 meter diameter parabola a gain of 7000 can be realized with a $1\frac{1}{2}^\circ$ half beam width at 10 megacycles. With the methods envisioned here, an antenna 2 or 3 miles in diameter may be feasible with a 25-fold increase in gain and a 5-fold decrease in beam width.

Parabolic Antenna with Inner Region Truncated

An improvement on a simple parabolic dust configuration would be obtained by removing an inner region by truncating it at an inner radius. The antenna pattern suffers little degradation by this truncation. On the other hand, the region removed is the one which has the greatest curvature, and in which deviations from the parabolic contour are most important. Hence it should be much easier to maintain the parabolic contour over the remainder of the reflecting surface which has relatively little curvature. Depending on the manner of formation of the dust contour, this truncated parabola may offer considerable simplification in containment.

Horn Antenna Dust Structures

A dust horn antenna would consist of four plane dust surfaces joined to form a waveguide. The waveguide width is flared towards an opening, permitting the signal volume inside the guide to expand toward the opening. Thus only plane dust surfaces need be formed for a dust horn antenna structure.

The flare of the horn may be in either dimension corresponding to an E plane horn if the taper is in the plane of the E vector (relative to the attached feed waveguide) or an H plane horn if the taper is in the H plane. Alternatively the taper may be in both directions and constitute a pyramidal horn. Table 14 gives the characteristics for optimum horns. Because of the dust structure one can consider horns which are very large compared with conventional ones. The conductive walls of the horn are here considered to be equivalent reflectors formed of dust which may provide complete wall area coverage. Alternatively, they may consist of individual dust beams providing a spaced coverage of the area. For the purpose of providing the correct phase distribution over the horn mouth, the horn must be very gradually tapered or flared. This provides that the phase front at the mouth of the horn shall be approximately planar rather than spherical. The smallest flare gives the sharpest beam and highest gain for a given mouth size. However, with the dust configuration thin and long (slow) tapers can be achieved. In Table 14 the symbol a is the H plane width and b the E plane width. ℓ is the length from the horn apex to the mouth.

Table 15 gives values of the gain, beamwidth, and required length of horn for 10, 30, and 100 megacycles.

Thus a horn type of dust configuration offers the possibility of high gain and small beam width. In this case, all reflective surfaces are planar, allowing for the use of dust containment schemes which are fundamentally different from that of the parabola.

TABLE 14

FORMULAS FOR OPTIMUM HORNS

	Horn Type		
	Pyramidal	Sectoral H-Plane	Sectoral E-Plane
Optimum Proportions	$a \approx \sqrt{3\ell\lambda}$ $b \approx 0.81\, a$	$a \approx \sqrt{3\ell\lambda}$	$b \approx \sqrt{2\ell\lambda}$
Property to be Optimized	gain	beamwidth in H plane	beamwidth in E plane
Half-Power Beam Widths (deg)			
H or (yz) plane	$\frac{80}{(a/\lambda)}$	$\frac{80}{(a/\lambda)}$	$\frac{68}{(a/\lambda)}$
E or (xy) plane	$\frac{53}{(b/\lambda)}$	$\frac{51}{(b/\lambda)}$	$\frac{53}{(b/\lambda)}$
Values of k for Calculation of Gain	0.50	0.63	0.65

Definitions: a = mouth dimension in z direction
b = mouth dimension in y direction
ℓ = horn length from mouth to apex

TABLE 15

GAIN, BEAMWIDTH, AND OPTIMUM HORN LENGTH VERSUS FREQUENCY

Horn Type	Frequency (10^6 cps)	a (m)	b (m)	ℓ (m)	Beamwidth H-Plane (degrees)	Beamwidth E-Plane (degrees)	Gain
Pyramidal	10	1000	810	11,000	2.4	2.0	5,600
	30	300	240	3,000	2.7	2.2	4,500
	100	300	240	10,000	0.8	0.7	50,000
Sectoral E-Plane	10	1000	7.5	11,000	2.4	200	65
	30	300	2.5	3,000	2.7	200	60
	100	300	0.75	10,000	0.8	200	190
Sectoral H-Plane	10	15	800	10,500	135	2.0	100
	30	5	300	4,500	135	1.7	120
	100	1.5	300	15,000	135	0.5	130

Fresnel Zone Plate Dust Antenna

Another interesting dust antenna structure is the Fresnel zone plate. This consists of a reflecting plate, portions of which have been removed to improve the diffraction pattern of the plate. (A complete flat plate reflector does not provide a useful antenna structure; it only provides an image of the antenna receiver feed in the plate, so that one may consider the resulting beam to be formed by two receiver feeds.) To use a flat plate reflector one should therefore remove portions of it to form a zone plate. The removed sections are the even (or odd) Fresnel zones. The removed portions are those which can cause destructive interference, i.e., portions from which rays to the focus would be π radians out of phase from the neighboring zones.

Experiments have been done[1] demonstrating the effectiveness of a Fresnel zone plate for x-band microwave radiation. These experiments show that the beamwidth for the Fresnel zone plate is almost identical with that of a paraboloid having the same diameter. This is one of the salient features of zone plates. Although the gain is much lower than that of a paraboloid of the same diameter, the beamwidth is the same.

The reason for the partial independence of gain and beamwidth is in the very nature of the zone plate as a diffraction device. Instead of scattering all of the incident radiation into the feed like a paraboloid, the zone plate scatters only a portion of it into the feed and hence, has a much lower gain. Beamwidth, on the other hand, is determined by the physical diameter.

Van Buskirk and Hendrix have compared gain equations with experimental data. Their results are given in Table 16.

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[1] Van Buskirk and Hendrix, "The Zone Plate as a Radio Frequency Focussing Element", IRE Transactions, A.P.G. p 319, May 1961

TABLE 16

GAIN VERSUS NUMBER OF ZONES FOR A ZONE PLATE ANTENNA

Number of Zones	Theoretical Gain (db)	Experimental Gain (db)
1	6.0	4.5
2	11.8	9.0
3	15.2	11.5

The total gain obtainable from a zone plate can be very high, since it will be approximately proportional to the diameter of the plate. The gain will be less than that of a paraboloid antenna, but it may be considerably simpler to form a flat zone plate dust structure than it is to form a dust parabola structure.

NASA-Langley, 1968 —— 32 CR-1136